Cosmological Expansion, Growth of Structure and Dark Energy

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Outline

Introduction

Cosmological timeline

WMAP results summary   SN Ia results summary

Case for dark energy

Dark energy phenomenology

Vacuum energy problem; Modification of GR?

Consistency tests

GR independent Expansion history

Future probes

Importance of alternate probes of dark energy

Gravitational lensing holds great promise

Amplitude of primordial density fluctuation

Scale Factor, Expansion Rate, ETC

Line element:

$$ds^2 = dt^2 - R(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right)$$

Scale Factor

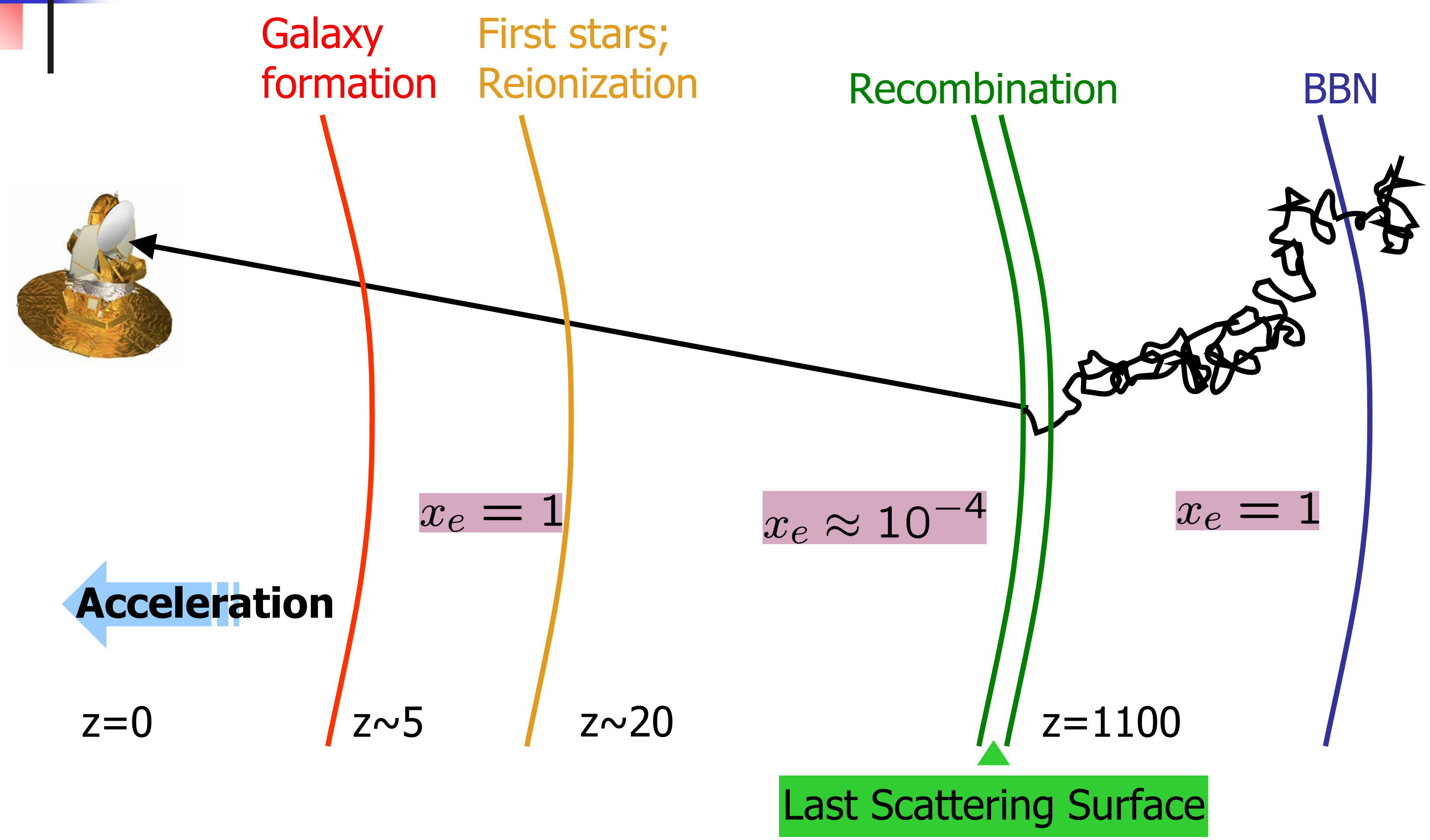
Redshift, z =1/R - 1

Sign of k determines the curvature of the universe.
k=0 is a flat universe.

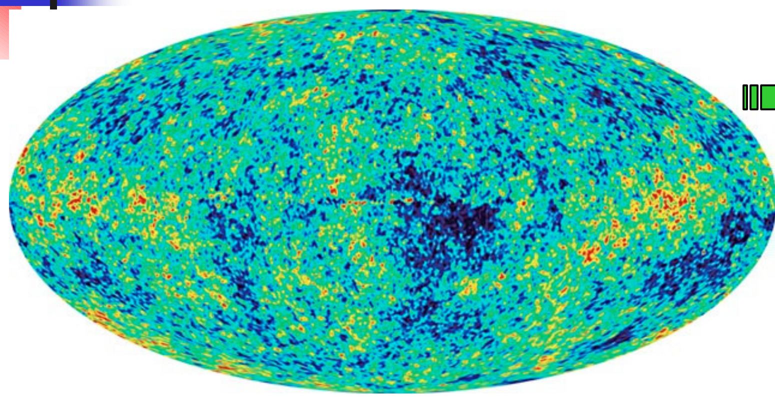
Expansion Rate: $H = \dot{R}/R$

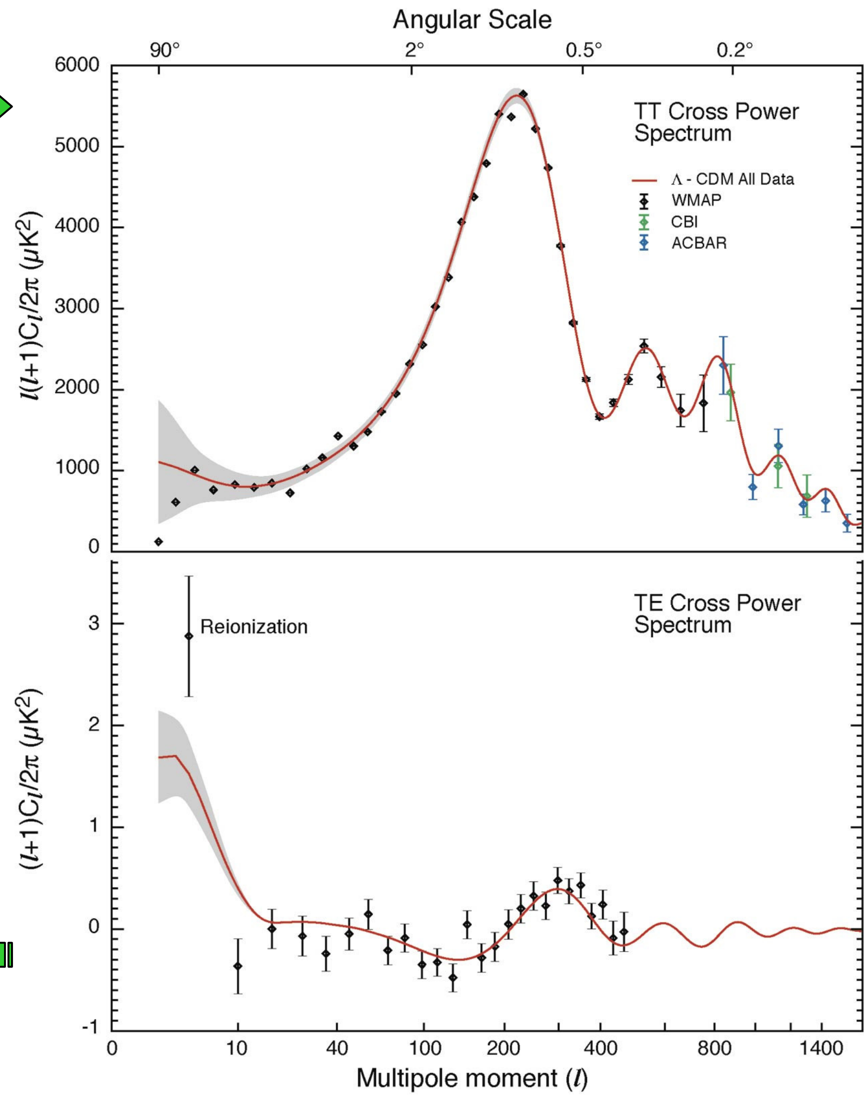
Acceleration: $\ddot{R}/R$

The Cosmological Timeline



CMB Observations : WMAP





Universe is close to being spatially FLAT.

95% of the universe is DARK! The rest (5%) is Baryons.

First stars formed when the Universe was about 1/20th the present size.

Supernova Ia observations

Measure apparent luminosity of a standard candle: Supernova Ia.
If we know the source luminosity, then we have the distance to the source.

$$\mathcal{L}(\text{measured}) = \frac{\mathcal{L}(\text{source})}{4\pi D^2}$$

For each source, we have a redshift.

$\lambda(\text{observed}) = \lambda(\text{source}) \times (1+z)$

Given a cosmology, D(z) is uniquely determined.

$\Downarrow$

Measured D(z) → Universe is Accelerating!
→ Presence of Dark Energy.

What is Dark Energy?

Qualitatively speaking …

- Dark energy does not have any SM interactions.
- It does not cluster strongly (if at all).
- It causes the acceleration of the universe; dark energy density changes slowly (if at all) as the universe expands.

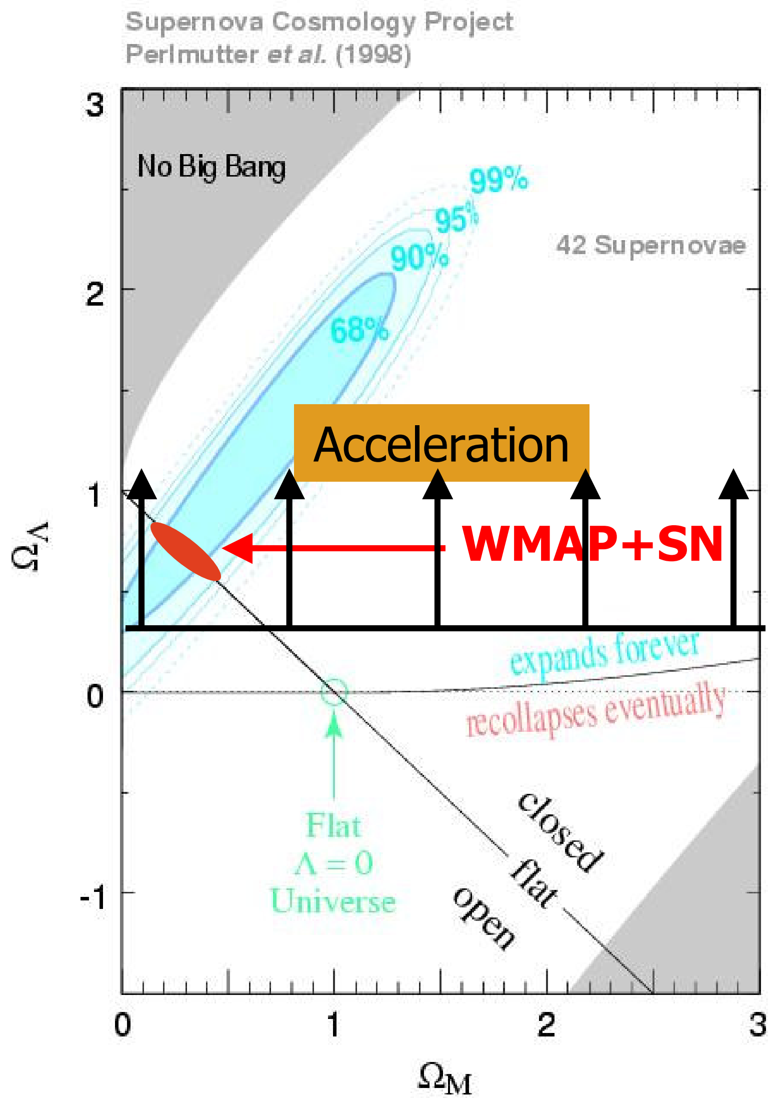
Acceleration occurs when

$$\frac{\ddot{R}}{R} = -\frac{4\pi}{3}\left(\frac{\rho + 3p}{\mathrm{m}_{\mathrm{pl}}^2}\right) > 0$$

$$\Rightarrow \frac{p}{\rho} < -\frac{1}{3}$$

Present data favor an accelerating universe.

Evidence for Dark Energy: Accelerating Universe



Assume dark energy is a cosmological constant.

Ω_M is the fraction of total density in matter.
Ω_Λ is the fraction of total density in the cosmological constant.

CMB: $\Omega_M+\Omega_\Lambda=1$

SNIa: $0.8\Omega_M-0.6\Omega_\Lambda=-0.2$

$\left.\right\} \Omega_M, \Omega_\Lambda$

Alternatives to an accelerating universe ?

- Axion dimming of supernovae

  Csaki, Kaloper & Terning, PRL 88 (2002) 161302

- Dust

  Aguirre, ApJ Lett 512 (1999) 19

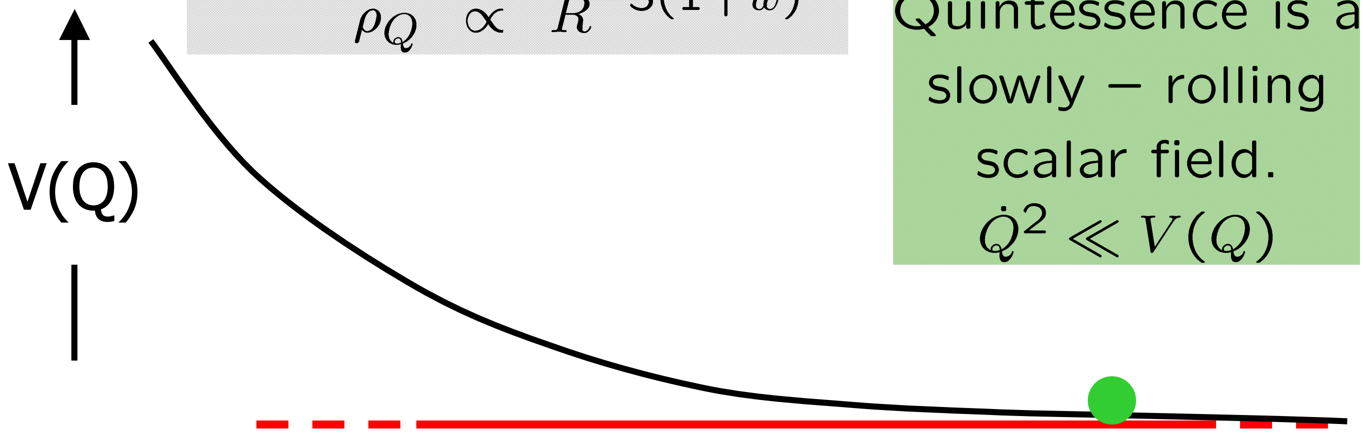
- Note that some form of energy density (apart from the matter density) is required to keep the universe flat.

- Future CMB data by itself will be able to verify or rule out the acceleration of the universe!

Dark Energy Phenomenology : Quintessence

$$w_Q = \frac{p_Q}{\rho_Q} \simeq -1 + \frac{\dot{Q}^2}{V(Q)}$$

$$\rho_Q \propto R^{-3(1+w)}$$



Quintessence is a slowly – rolling scalar field. $\dot{Q}^2 \ll V(Q)$

Cosmological Constant
V(Q) = constant

Clustering built – in.

Psuedo Nambu-Goldstone bosons as quintessence
Frieman, Hill, Stebbins & Waga, PRL 75 (1995) 2077

But Seriously … What is Dark Energy?

Observable : Function (Expansion Rate)

GR postulates :

$$\rho = \frac{3\mathrm{m}_{\mathrm{pl}}^2}{8\pi}\left[\left(\frac{\dot{R}}{R}\right)^2 + \frac{k}{R^2}\right]$$

$$p = \frac{-\mathrm{m}_{\mathrm{pl}}^2}{8\pi}\left[2\frac{\ddot{R}}{R} + \left(\frac{\dot{R}}{R}\right)^2 + \frac{k}{R^2}\right]$$

A perfectly smooth component of energy and pressure cannot be detected in any way except for its influence on the expansion rate.

If not a cosmological constant, then dark energy must cluster.

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Trouble on the Horizon …

Standard model of cosmology is remarkably successful, but for the vacuum energy and dark energy problems.

Vacuum energy problem

$$\rho_{\text{present}} \approx \rho_{\text{crit}} \equiv \frac{3}{8\pi} \mathrm{m}_{\text{pl}}^2 H_0^2 = \boxed{10^{-47}\,\mathrm{GeV}^4}$$

$$\rho_{\text{vac}} \approx \mathrm{m}_{\text{pl}}^4 = \boxed{10^{76}\,\mathrm{GeV}^4} \quad (\text{or at least } \mathrm{m}_{\text{susy}}^4 \approx \boxed{\mathrm{TeV}^4})$$

Dark energy problem

What sets the dark energy scale ~ $\rho_{crit}^{1/4}$ ~ milli-eV?
Or equivalently, why now?

Dodelson, Kaplinghat and Stewart, *Solving the coincidence problem*, PRL 85, 3335 (2000)

Modify Gravity on Horizon Scales ?

- The possibilities …

$$H^2 = \frac{8\pi\rho}{3\mathrm{m}_{\mathrm{pl}}^2} - \frac{k}{R^2} + \frac{\text{``}\Lambda\text{''}}{3}$$

- Self-tuning branes

  Arkani-Hamed, Dimopoulos, Kaloper & Sundrum, Phys Lett B480 (2000) 193

- Leakage into extra dimensions

  Dvali, Gabadadze & Shifman, hep-th/0202174

- Non-local modification of gravity

  Arkani-Hamed, Dimopoulos, Dvali & Gabadadze, hep-th/0209227

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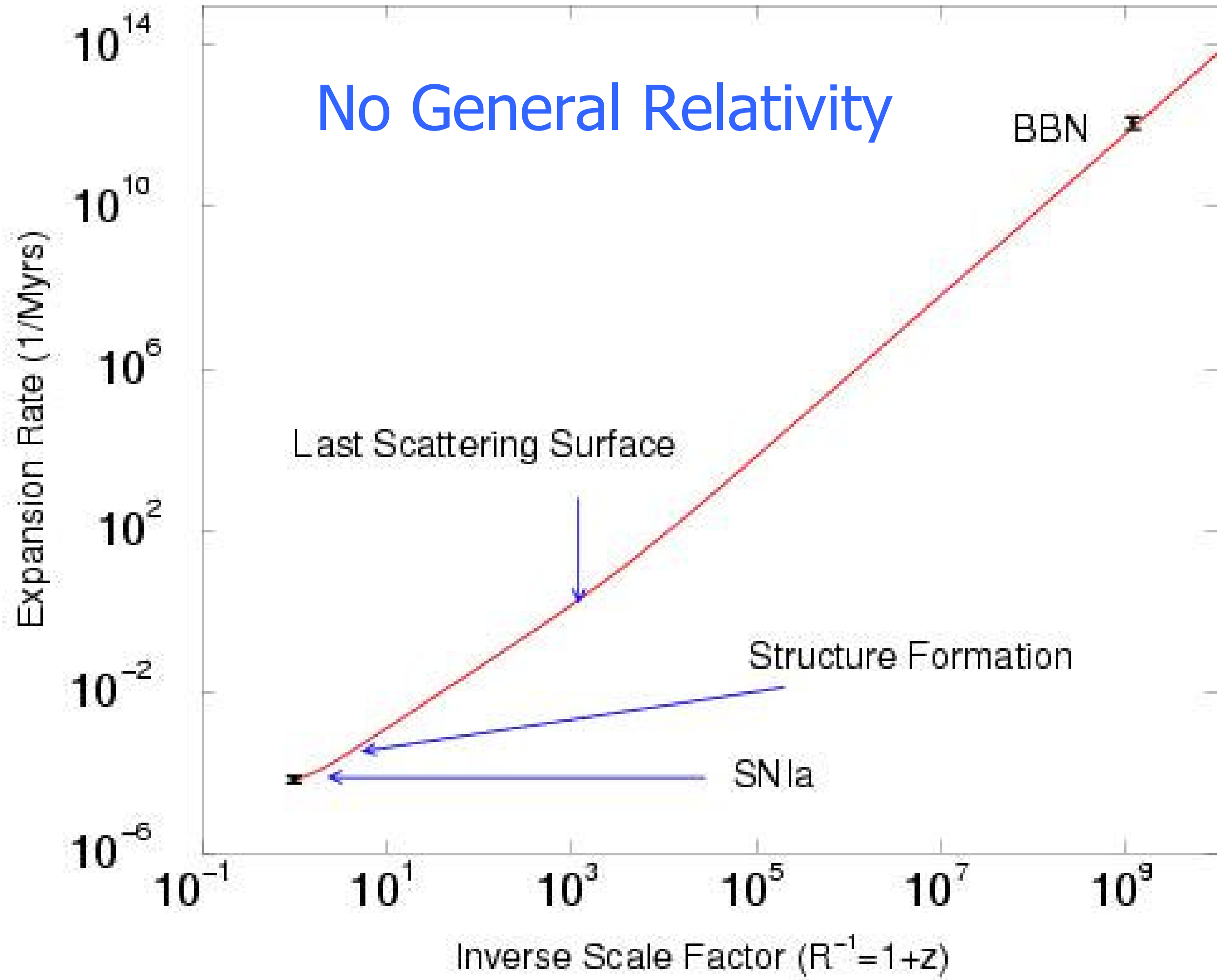
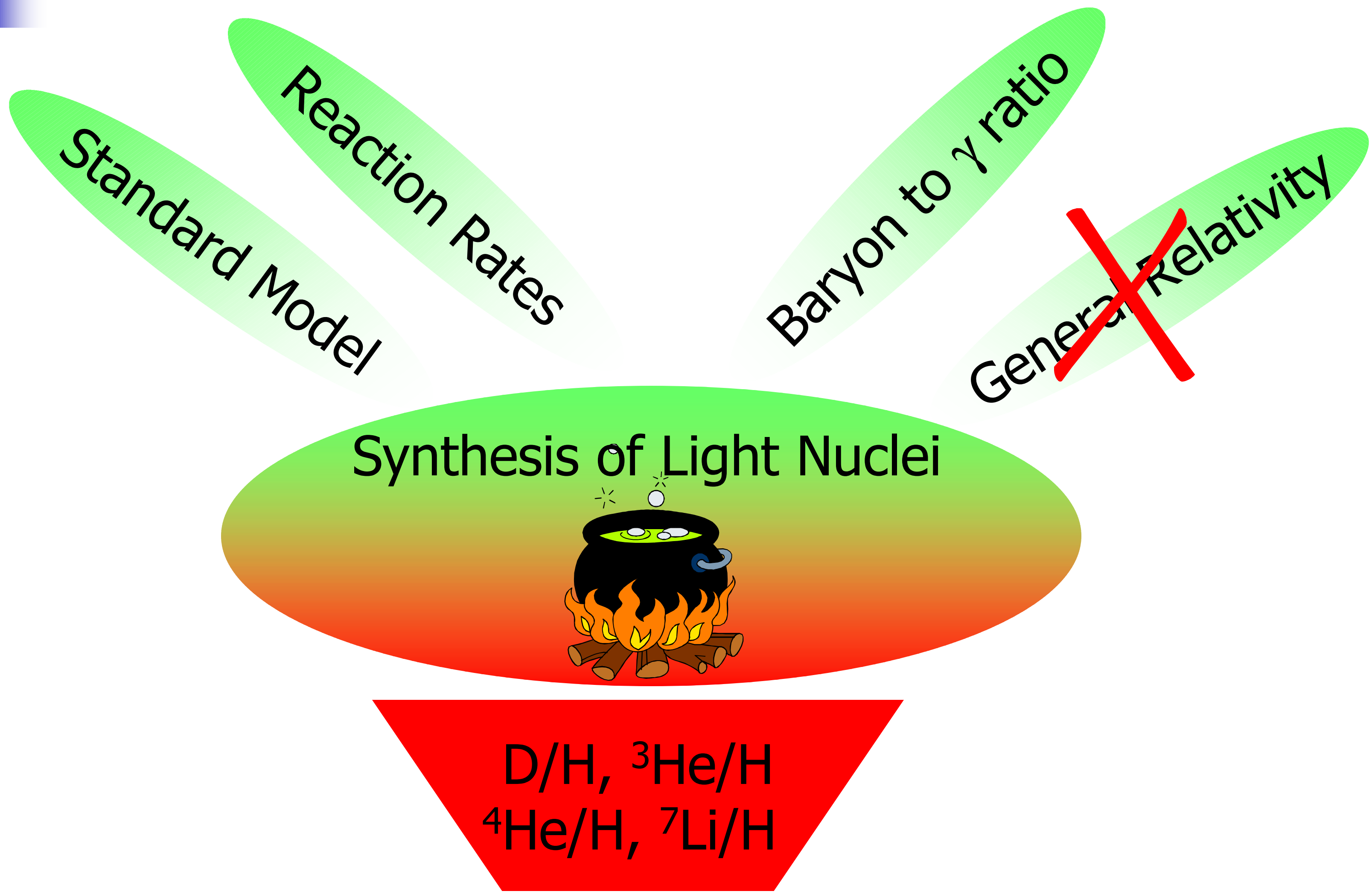
Consistency Tests: Expansion History

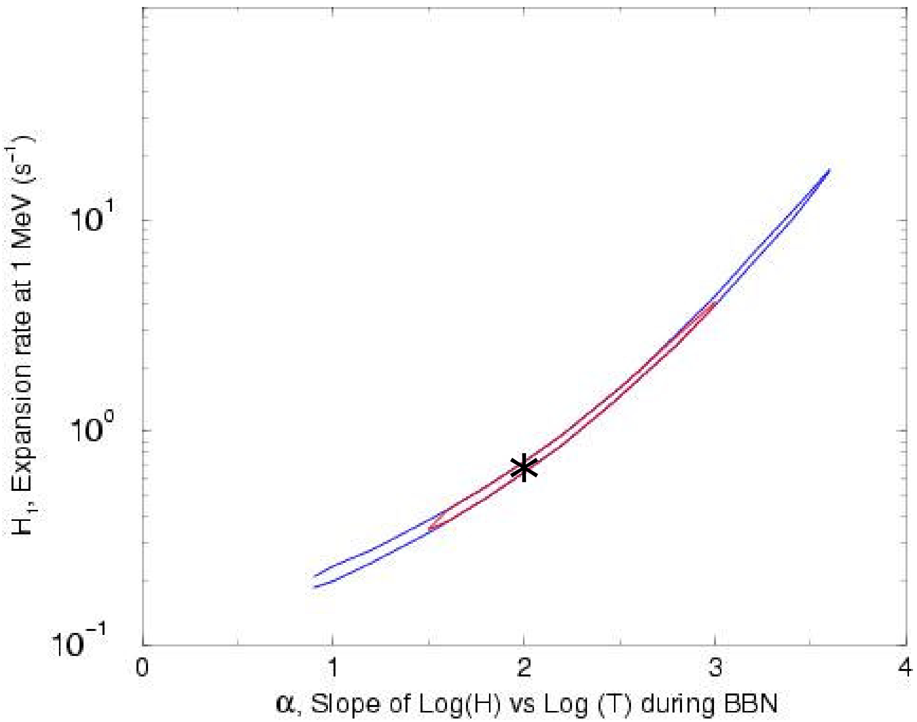


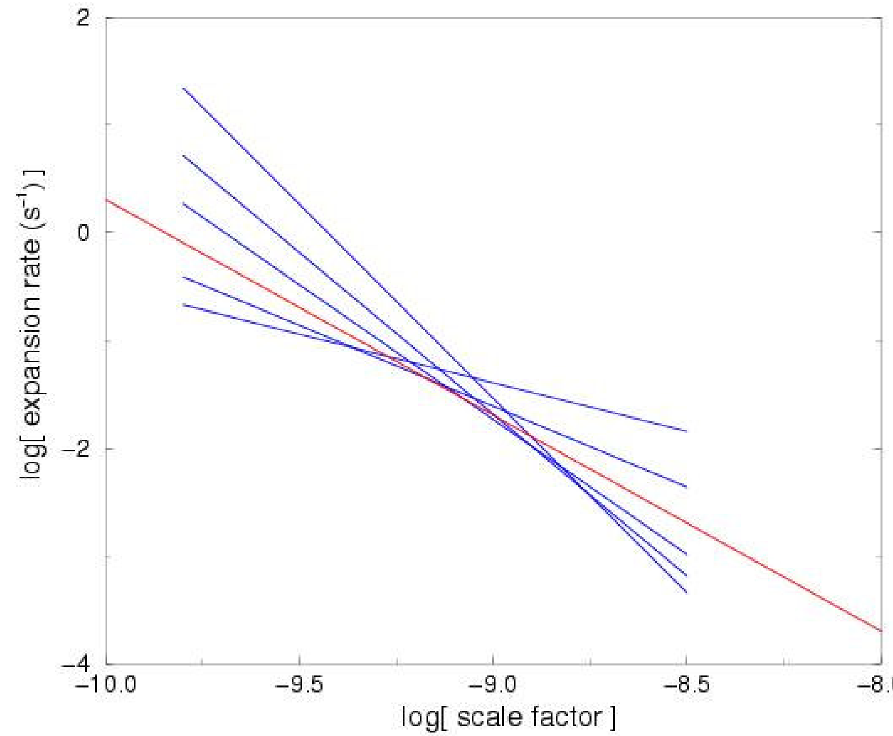
Big Bang Nucleosynthesis



Expansion Rate of the Universe During BBN

No General Relativity!
Minimal assumptions.

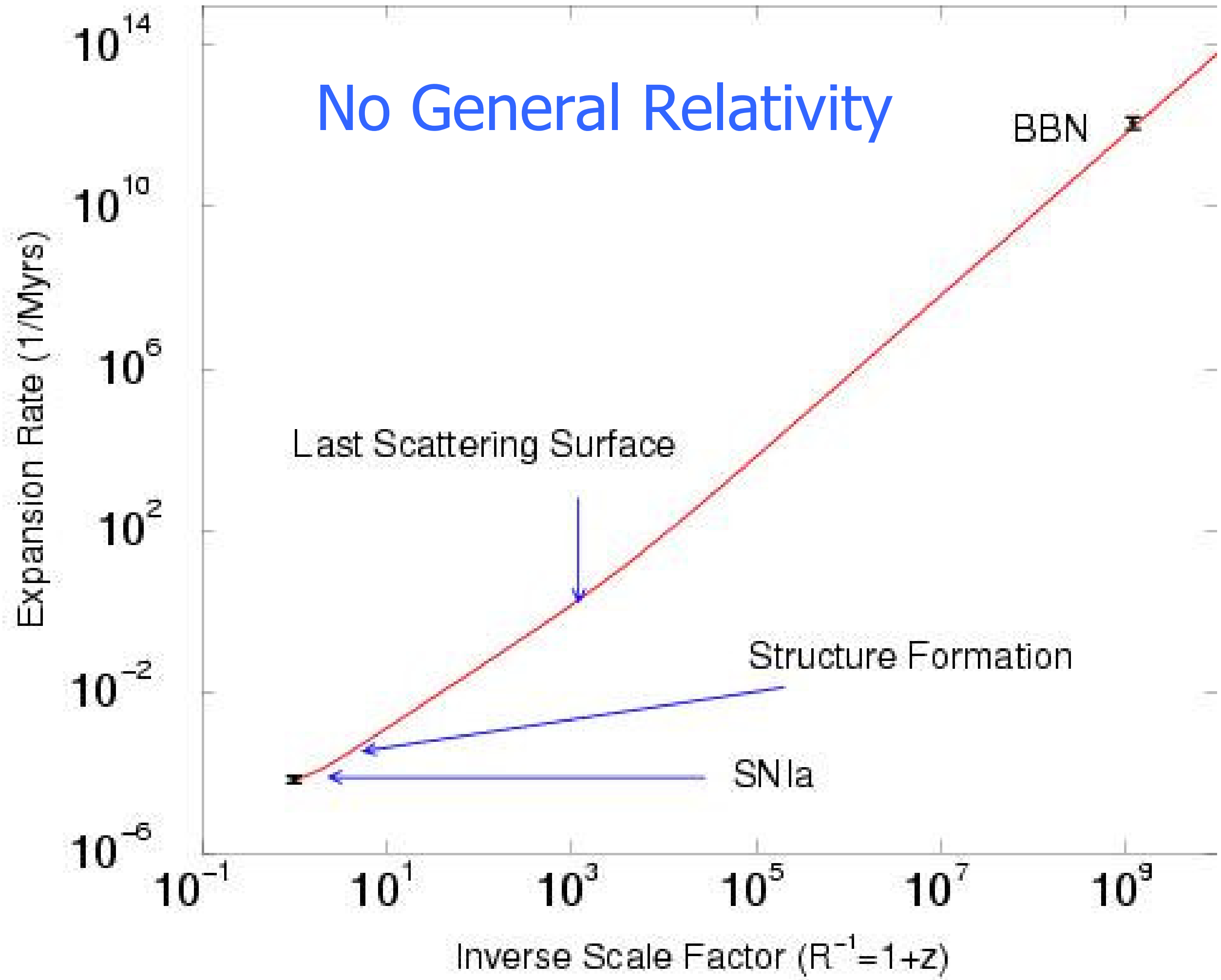




Expansion rate at 200 keV constrained to about 30% of the standard BBN value.

Carroll and Kaplinghat, PRD 65, 063507 (2002)

Consistency Tests: Expansion History



Growth of Structure and Expansion Rate

- CMB
  - Distance to last scattering surface
  - Sound horizon when photons last scattered
  - Collisional (Silk) damping

- Large scale structure
  - Growth of perturbations is hindered by a larger expansion rate since the expansion rate acts like a friction term.

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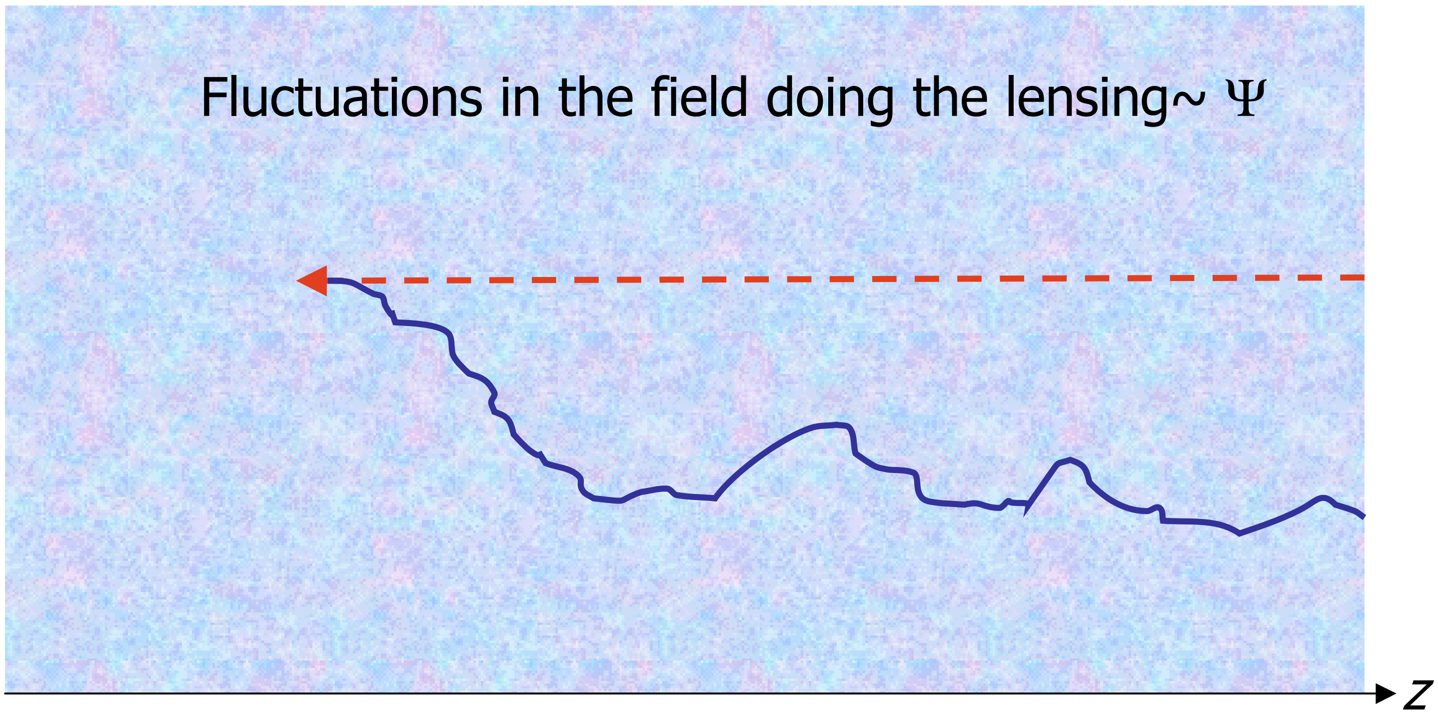
Alternate Probes of Dark Energy

- Probe the growth of structure as well as the expansion rate.

- Why do we need to go beyond SNIa magnitude-redshift relation?
  - Different systematic
  - Test alternate hypothesis (like axion dimming, dust)
  - Test clustering properties of dark energy

- Alternate probes:
  - Weak lensing of the CMB
  - Weak lensing of galaxies
  - Number counts of clusters

Gravitational Lensing



$$\phi = \int dz\, \mathscr{P}(z)\Psi(z)$$

Averaged fluctuation along the geodesic.

Weak Lensing and Dark Energy

Lensing breaks degeneracies in the primary CMB.

Distances to lens and source ← Expansion history

$$\phi = 2\int dr \frac{r - r_{\mathrm{ls}}}{r\, r_{\mathrm{ls}}} \Psi(r)$$

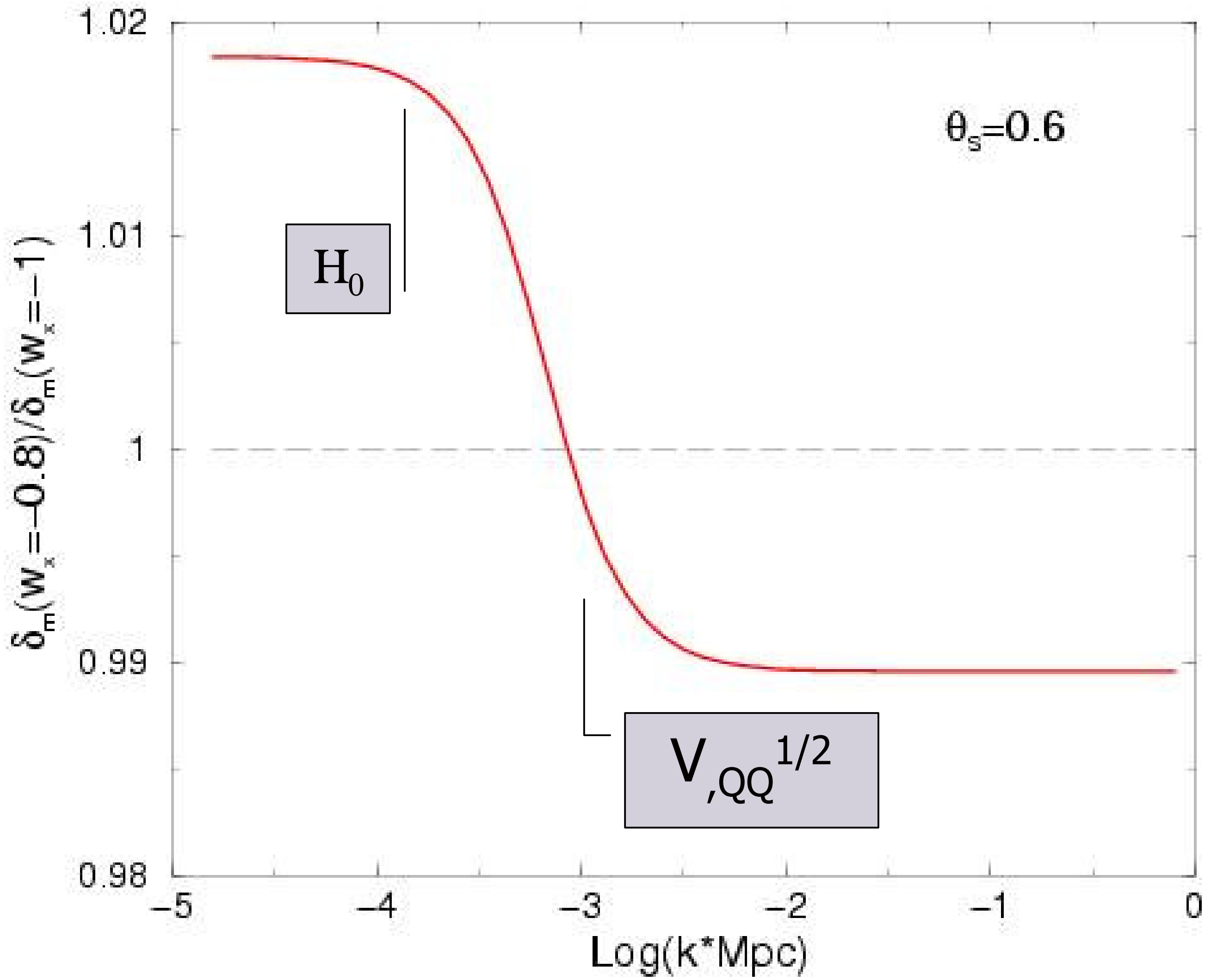
P_Ψ

m_ν

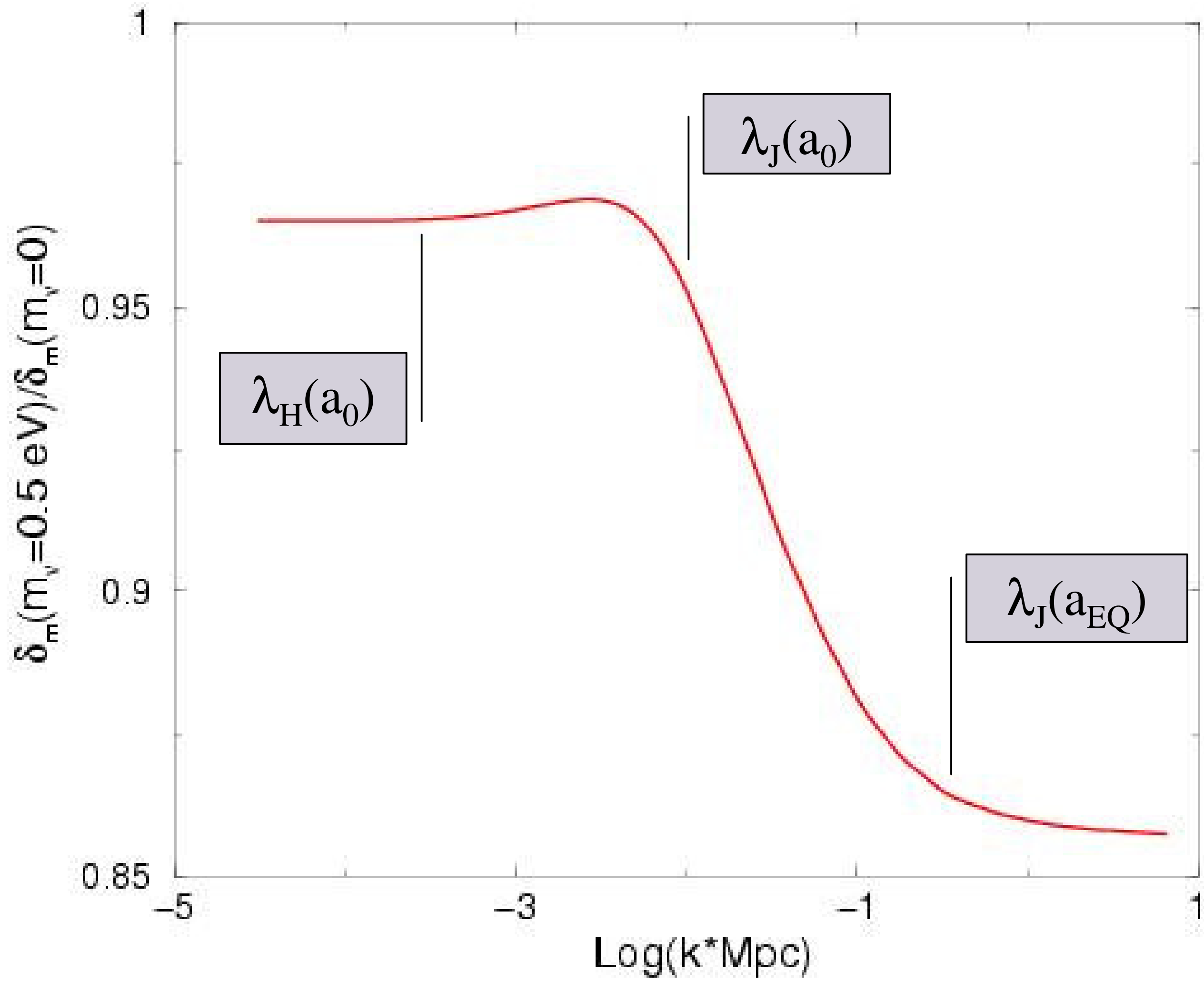
w_x

Fluctuations in mass density

Effect of Dark Pressure



Effect of a Massive Neutrino

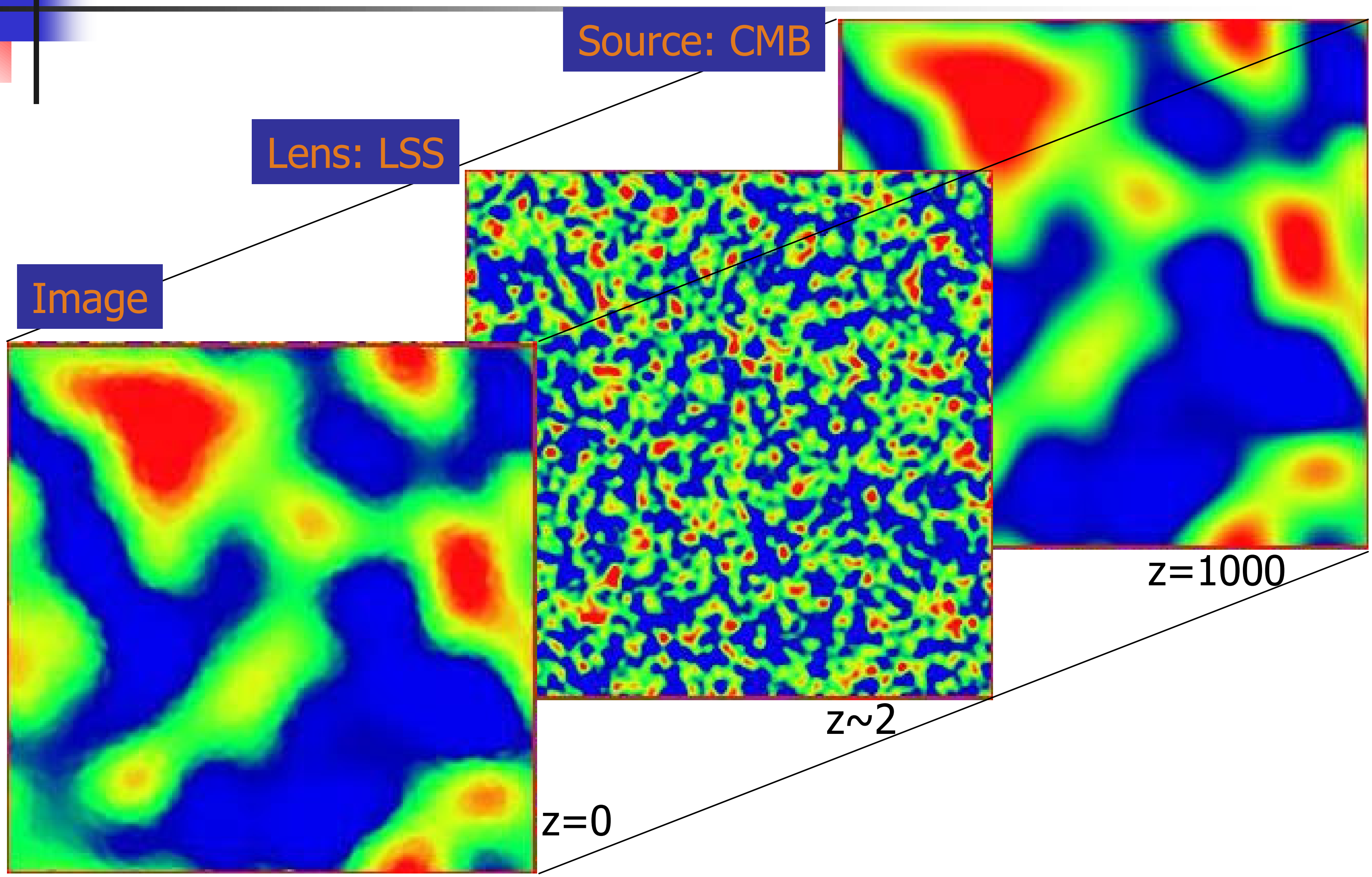


Galaxy Lensing Tomography

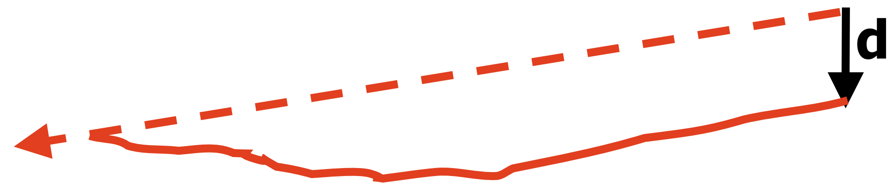
- Weak lensing distorts the shape of galaxies. This distortion is measurable when averaged over a large number of galaxies.
- The distortion (shear) depends on the projected mass density along the photon's geodesic, Ψ.
- Look at the shear of galaxies in specific redshift bins. This provides the redshift evolution of the projected mass density, Ψ, which depends (among other things) on dark energy and neutrino mass.
- The power spectrum at early times (recombination) has to be well constrained for the above to work.

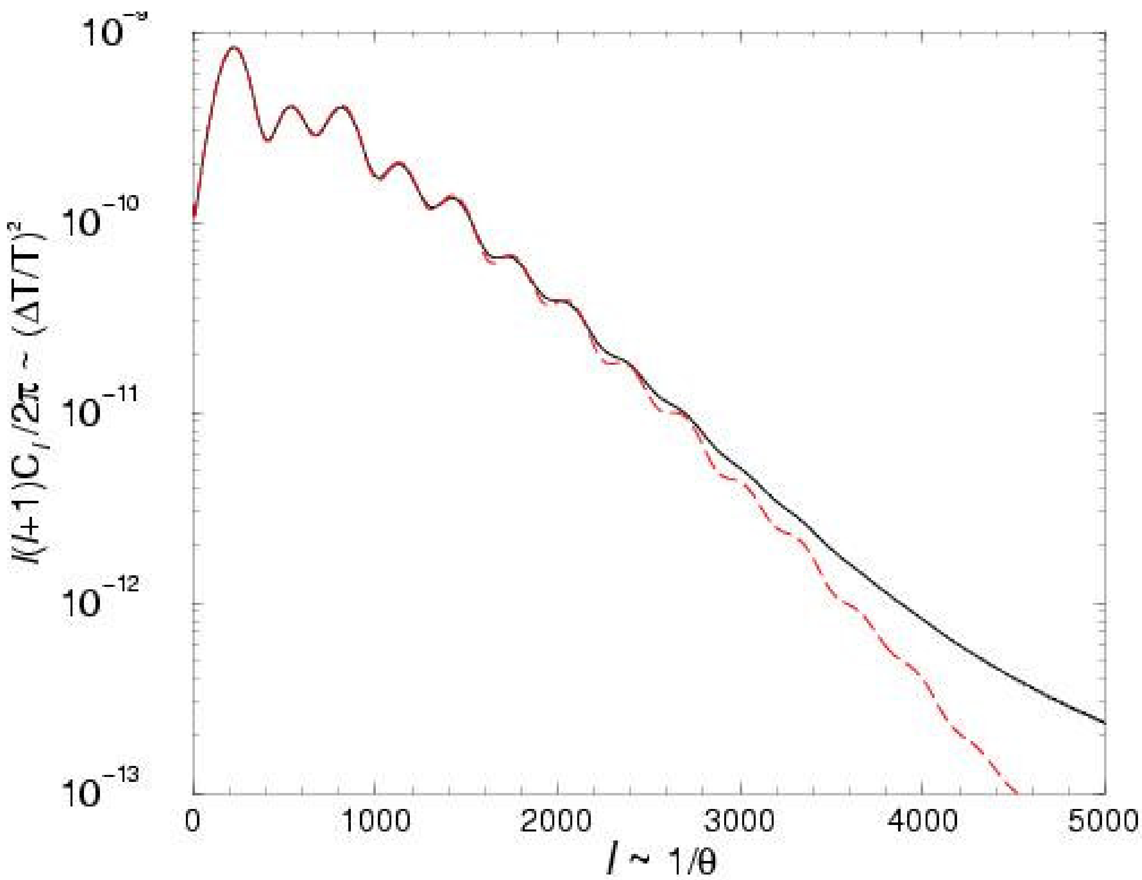
Hu and Keeton, 2002

Lensing of the CMB



Effect of Lensing on CMB Power Spectrum



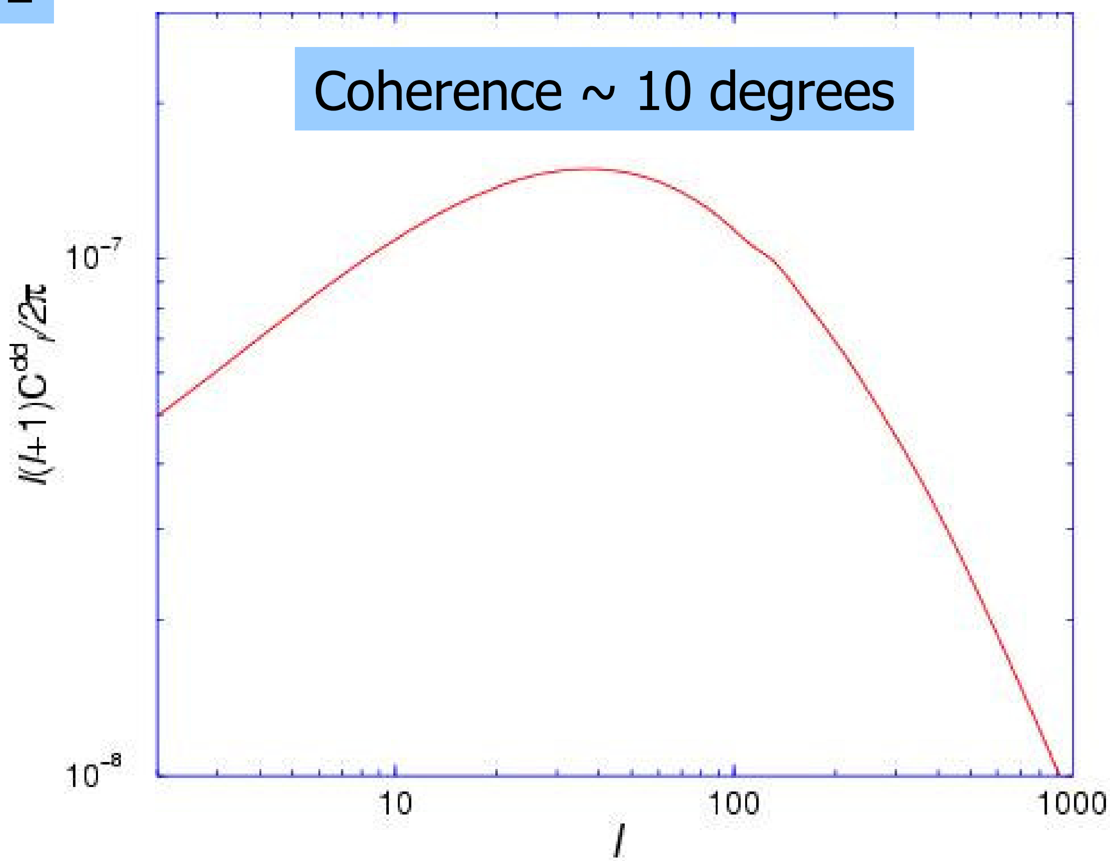


$$T(\vec{n}) = \tilde{T}(\vec{n} + \vec{d})$$
$$\vec{d} = \vec{\nabla}\Phi$$

Deflection ~ arcminute

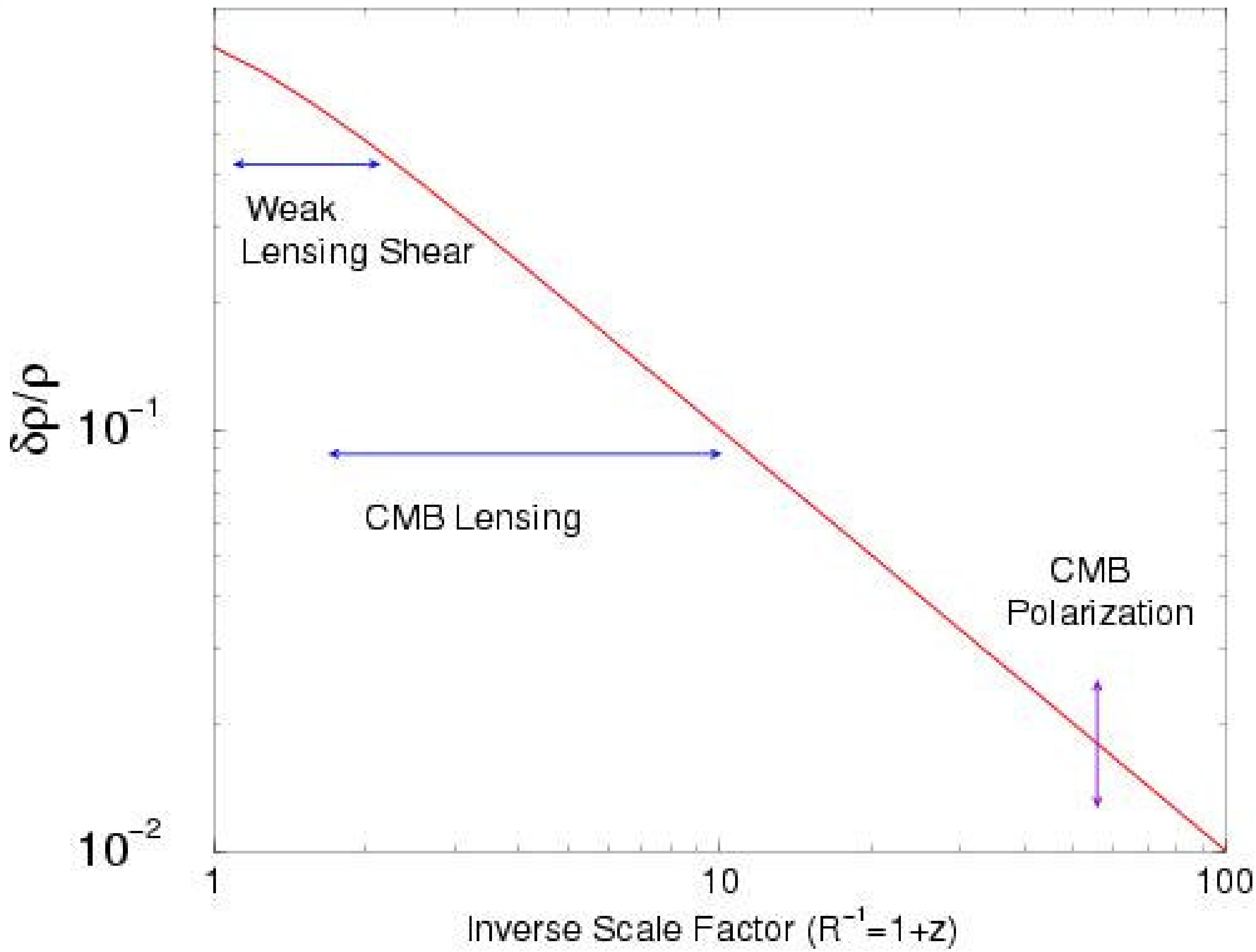
Coherence of Lensing Deflection

Peak sensitivity ~ z=2



$$T(\vec{n}) = \tilde{T}(\vec{n} + \vec{d})$$
$$\vec{d} = \vec{\nabla}\Phi$$

Growth of Structure: Probing Dark Energy



Amplitude of the Primordial Power Spectrum

- To isolate the effects of dark energy at low redshifts, we must pin down the power spectrum of the gravitational potential at high redshifts.
- The amplitude of the power spectrum, A, is degenerate with the optical depth to the last scattering surface. One way to break this degeneracy is to measure the reionization signature in CMB polarization at large angles.
- Our ignorance of how reionization occurred adds to the measurement uncertainty for the optical depth. However, there is enough information in the large angle CMB polarization signal that this will not be the limiting factor.
- Planck will be able to constrain the optical depth to about 0.005 which implies that the amplitude of the primordial power spectrum can be constrained to about 1%.

Kaplinghat et al, *Probing the reionization history of the universe using CMB polarization*, ApJ (2002)

So… What Will It Take?

Experiment	l^T_{max}	$l^{E,B}_{\text{max}}$	ν (GHz)	θ_b	Δ_T	Δ_P
Planck	2000	3000	100	9.2'	5.5	∞
			143	7.1'	6	11
			217	5.0'	13	27
SPTpol ($f_{\text{sky}} = 0.1$)	2000	3000	217	0.9'	12	17
CMBpol	2000	3000	217	3.0'	1	1.4

This is what it will take to measure primordial tensor perturbations down to T/S ~ 10^{-5}

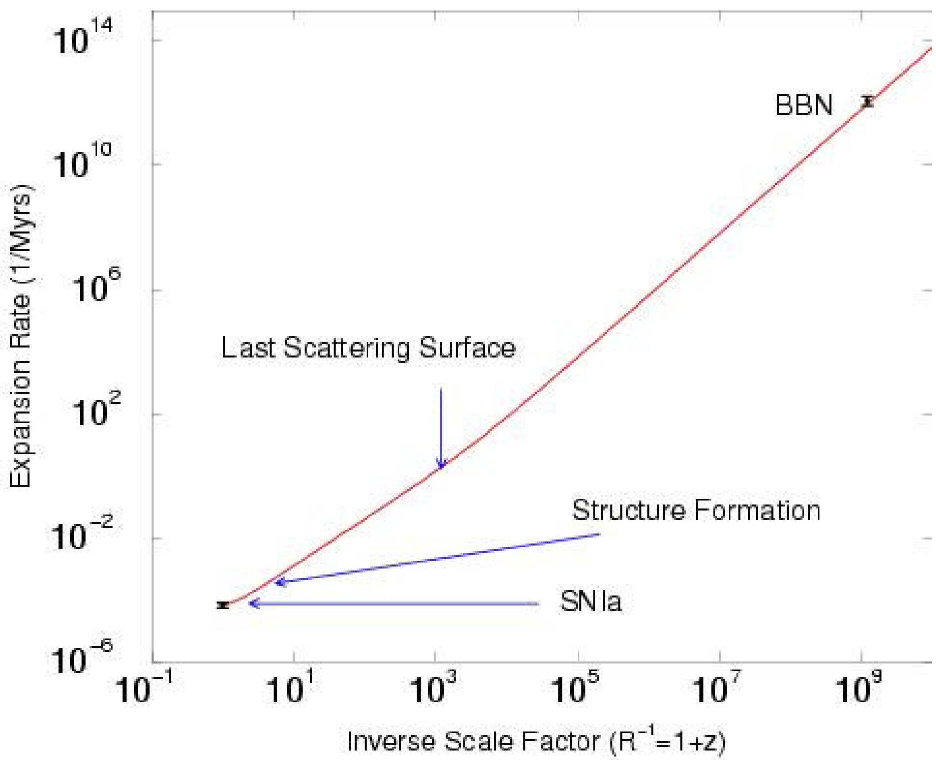
Kaplinghat, Knox and Song, 2003

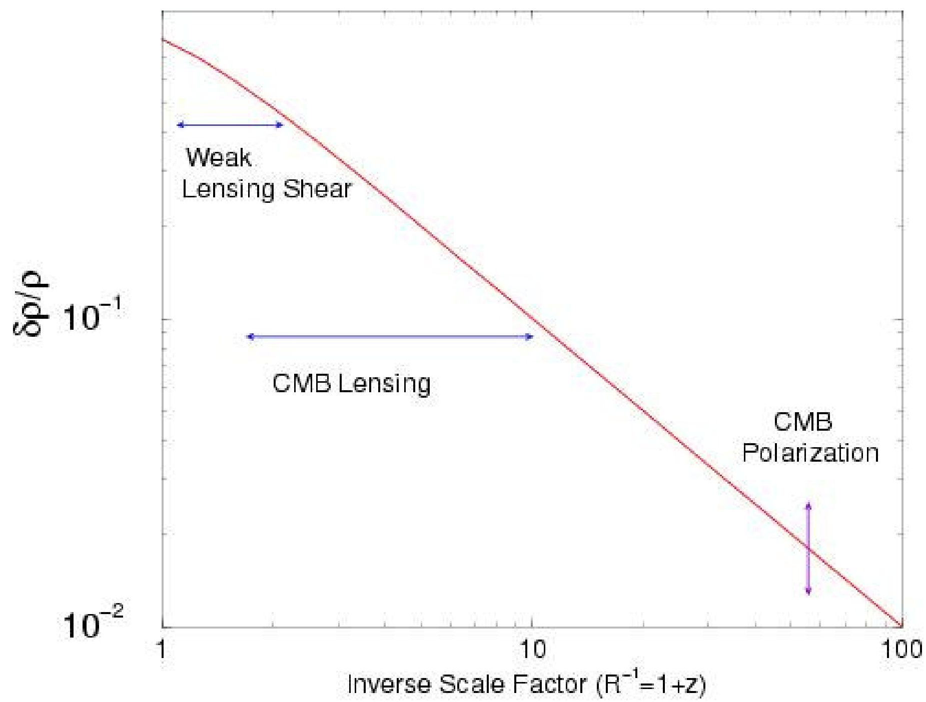
Fundamental Physics with CMB Lensing

- Detect the acceleration of the universe with CMB alone, at 5σ.
- Measure energy scale of inflation down to about 2×10^{15} GeV.
- $\sigma(m_\nu) \approx 0.03$ eV. This should be compared to the expectation for the sum of neutrino masses being greater than 0.06 eV.
- Precision measure of the amplitude of scalar perturbations to 1%.
- Tilt and its variation with scale. Vital for differentiating between hybrid inflation models.
- Map reionization history.

Summary : Conceptual Cosmology Bottom-Up

The standard cosmological model is remarkably successful but we do not understand all its ingredients.





Important to check for consistency within the standard cosmological model and to probe the nature of dark energy in different ways.